First On-Wafer Power Characterization of MMIC Amplifiers at Sub-Millimeter Wave Frequencies

A. K. Fung, *Member, IEEE*, T. Gaier, L. Samoska, *Senior Member, IEEE*, W. R. Deal, *Senior Member, IEEE*, V. Radisic, *Senior Member, IEEE*, X. B. Mei, W. Yoshida, P. S. Liu, J. Uyeda, M. Barsky, and R. Lai

***Abstract*—We present on-wafer power measurements of 35 nm gate length InP HEMT amplifiers at 330 GHz. Various amplifiers are examined. The maximum output power of 1.78 mW is measured from a three stage amplifier. Additional output power may be possible but limited by our input power source level to saturate amplifiers. This result is the highest frequency on-wafer power measurement we are aware of reported to date, and demonstrates the technique we utilize to be a fast method of evaluating power performance of submillimeter wave amplifiers without the need to package devices.**

***Index Terms*—Amplifier, monolithic microwave integrated circuit (MMIC), MM-Wave, power measurement.**

I. Introduction

RECENT developments in semiconductor technology have enabled advanced submillimeter wave (>300 GHz) transistors and circuits [1]–[3]. These new high speed components have required new test methods to be developed for characterizing performance, and to provide data for device modeling to improve designs. Current efforts in progressing high frequency testing have resulted in on-wafer S-parameter measurements up to approximately 340 GHz [4] and swept frequency vector network analyzer waveguide measurements to 508 GHz [5]. On-wafer noise figure measurements in the 270–340 GHz band have been demonstrated [6]. In this letter we report on on-wafer power measurements at 330 GHz of a three stage amplifier that resulted in a maximum measured output power of 1.78 mW and maximum gain of 7.1 dB. The method utilized demonstrates the extension of traditional power measurement techniques to submillimeter wave frequencies, and is suitable for automated testing without packaging for production screening of submillimeter wave circuits.

II. 330 GHz Input/Output Power Test Set

The schematic diagram of the test set is shown in Fig. 1. The test signal is generated with a Gunn oscillator and maximized by a W-band amplifier. A WR10 variable attenuator is used for varying the input power $(P_{\rm in})$ level of the test signal. To reach the test frequency, a frequency tripler is used to multiply up the Gunn oscillator frequency. To transition between waveguide mode, into and out of the CPW wiring environment of the device under test (DUT), recently developed, commercially available WR3 probes are used [4]. Output power $(P_{\rm out})$ from the DUT is measured with an Erickson PM2 calorimeter. An one inch linearly tapered waveguide is used to transition from the output WR3 CPW probe to the input WR10 port of the calorimeter.

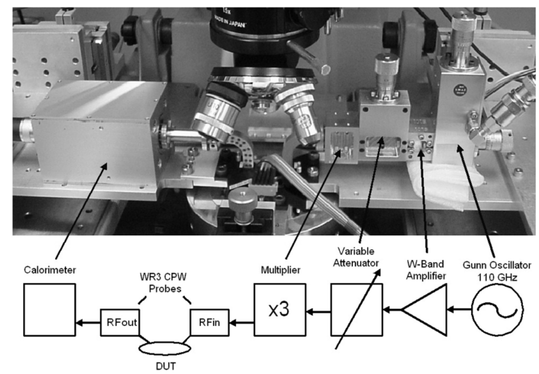

Fig. 1. Schematic diagram of the 330 GHz power measurement test set. The test signal power level is maximized with an in-house JPL amplifier and adjusted with a variable attenuator. The Gunn signal frequency is tripled with a VDI multiplier. GGB Inc. WR3 CPW probes are used to transition between waveguide and the on-wafer CPW wiring environment. Output power is measured with an Erickson PM2 calorimeter.

The Erickson PM2 calorimeter for measuring power is used with the manufacturer's calibration. Three adjustments are made prior to measurements at 330 GHz. The power measurement scale is set to 20 mW, the calibration factor dial is set to remove loss of the calorimeter's internal input waveguide element, and the meter is zeroed. We have cross referenced power measurements at 110 GHz with an Agilent power meter, and found measurements to be consistent to about 3%. Return loss of the calorimeter with an one inch waveguide transition to WR3 or WR2.2 is better than approximately -20 dB across the WR3 or WR2.2 frequency bands (see Fig. 2), and represents a reasonable load at the test frequency.

At the DUT input and output reference planes, the test set is fundamentally limited by the frequency and power level stimulus that can be supplied to, and measured from there. The lower frequency limit of the current test set is 330 GHz, due to the lower limit of the Gunn oscillator (110 GHz). The upper frequency limitation is due to the WR3 CPW probe bandwidth, which we have operated at an extended frequency of up to about 340 GHz. The maximum input power level at 330 GHz is approximately -1.0 dBm. It is limited by the output power from

Manuscript received November 21, 2007; revised January 3, 2008. This work was supported by the DARPA SWIFT Program and Army Research Laboratory under ARL Contract W911QX-06-C-0050 and by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

A. Fung, T. Gaier, and L. Samoska are with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA 91109, USA (e-mail: andy.k.fung@jpl.nasa.gov).

W. R. Deal, V. Radisic, G. Mei, W. Yoshida, P. S. Liu, J. Uyeda, M. Barsky, and R. Lai are with the Northrop Grumman Corporation, Redondo Beach, CA 90278 USA.

Digital Object Identifier 10.1109/LMWC.2008.922713

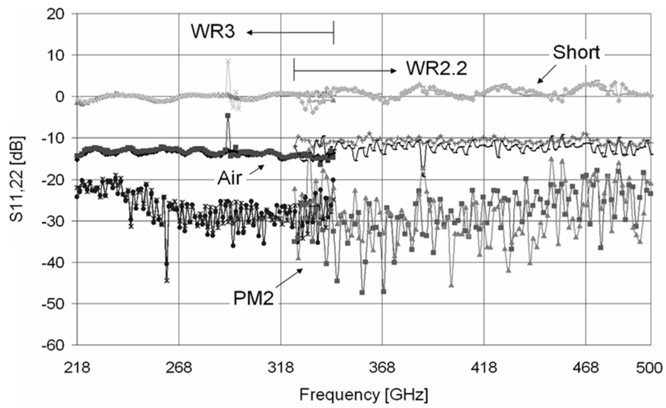

Fig. 2. S-parameter measurements of return loss of the Erickson PM2 calorimeter with an one inch WR3 or WR2.2 to WR10 transition. The calorimeter has a WR10 input port. Measurements of Shorts and open waveguide ports to air are provided for reference.

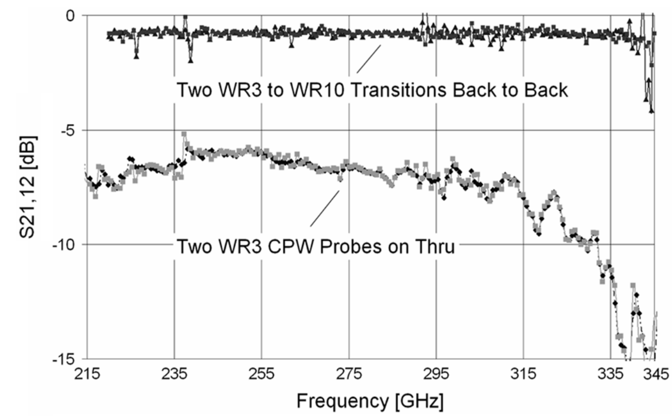

Fig. 3. S-parameter measurement of insertion loss of two WR3 CPW probes on a 175 μm Thru standard and two WR3 to WR10 transitions placed back to back. Loss per probe and per transition can be calculated by dividing the loss measurements by a factor of two.

the W-band amplifier plus loss from the variable attenuator, multiplier and input WR3 probe. Minimum input power level can be negligibly set with the variable attenuator. Maximum power level that may be measured at the output is 28 dBm and is set by the recommended calorimeter rating plus buffering loss from the WR3 CPW probe and the WR3 to WR10 waveguide transition to the calorimeter. The minimum measurable output power level is dependant on the calorimeter measurement scale setting that we used (20 mW) and limited by the test environment. Taking into account waveguide transition loss, output probe loss, the minimum measurable output power at the DUT reference plane is about -18 dBm.

The frequency range of the test set may be extended by utilizing other commercially available parts such as a different Gunn oscillator, multiplier and/or amplifier. However the ultimate upper frequency range is currently limited by the commercially available WR3 CPW probe, with a bandwidth of about 220–340 GHz. The minimum measurable output power should also be improved by better environmental control and utilizing the lowest PM2 calorimeter measurement scale setting for lower power measurements.

III. Input and Output Power De-Embedding

To determine $P_{\rm in}$ versus $P_{\rm out}$ performance of a DUT, power levels need to be de-embedded to the input and output of the DUT reference plane. To determine $P_{\rm in}$, the output power level from the tripler at 330 GHz is first measured in waveguide with the calorimeter, and the input WR3 CPW probe loss to the DUT is subtracted out. $P_{\rm out}$ is measured with the test configuration in Fig. 1 and similarly the output probe loss and the waveguide transition between the CPW probe and the calorimeter are subtracted out. This is done for all variable attenuator $(P_{\rm in})$ test settings.

Probe loss has been characterized in two ways. One method measures the S-parameters of the WR3 CPW probes connected through a GGB Industries Inc. 175 μm CPW Thru line standard (Fig. 3), and half the measured insertion loss is attributed as probe loss per probe. At 330 GHz this gives -5.04 ± 0.09 dB per probe. The error is derived from the difference in dB of values used to calculate the average probe loss. In the second method, we measure probe loss with the test set in Fig. 1. By dividing in half the net loss incurred by insertion of both probes and the 175 μm Thru line as the DUT, we deduce a probe loss of -5.02 ± 0.45 dB. Here the probe loss is the average value taken when the WR3 CPW probes are interchanged between the input source side and the output measurement side. The error is the difference between the measurements from the average value.

The loss of the WR3 to WR10 transition used between the CPW output probe and calorimeter can also be deduced similarly to the CPW probe loss. Placing two transitions back to back on the WR10 side, S21 and S12 measurements divided by two gives an average loss per transition of -0.42 ± 0.02 dB at 330 GHz (see Fig. 3). The error in the measurement is the deviation of the insertion loss measurements from the average. Using the power test set of Fig. 1, average loss of the back-to-back transitions can also be measured. Repeated measurements give loss per transition of -0.40 ± 0.01 dB. The error here is due to irreproducibility of the flange connections.

To deduce $P_{\rm in}$, $P_{\rm out}$ and gain from measurements of an amplifier DUT, probe losses and the waveguide transition to the calorimeter loss must be de-embedded to determine the power levels at the input and output probe pads of the DUT. In this letter we use the probe loss and transition loss data deduced with the Fig. 1 power measurement test set and equipartitioning of probe loss for calculating amplifier characteristics.

IV. Measured Results

$P_{\rm in}$ versus $P_{\rm out}$ are measured for a variety of devices at 330 GHz. The greatest $P_{\rm out}$ result came from a three-stage power amplifier [7] at bias conditions with all the drain voltages at 1.46 V, net drain current of 70.5 mA, all gate voltages at 0.30 V, and net gate current of 95.2 μA. Fig. 4 shows $P_{\rm out}$ and gain, with error bars, versus $P_{\rm in}$ after de-embedding probe and transition losses. A maximum $P_{\rm out}$ of 2.52 ± 0.49 dBm (1.78 mW) and maximum gain of 7.07 dB are measured. The maximum gain from power measurements is near the measured small signal S-parameter gain of 7.01 dB at 330 GHz from VNA tests of another copy of the same three-stage amplifier.

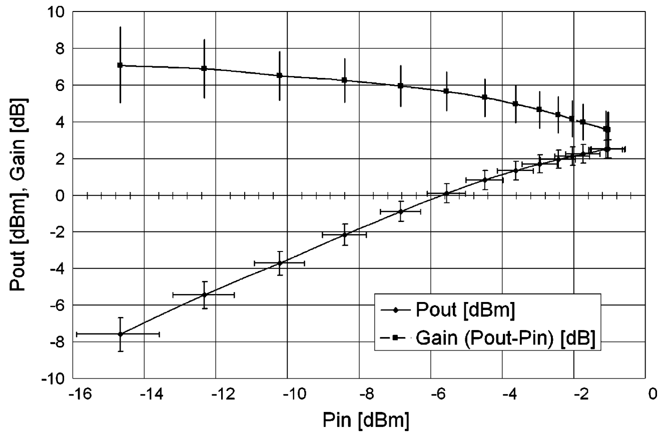

Fig. 4. $P_{\rm out}$ and Gain versus $P_{\rm in}$ of a three-stage InP HEMT amplifier (Power270) at 330 GHz. Error bars are shown at each power measurement data point.

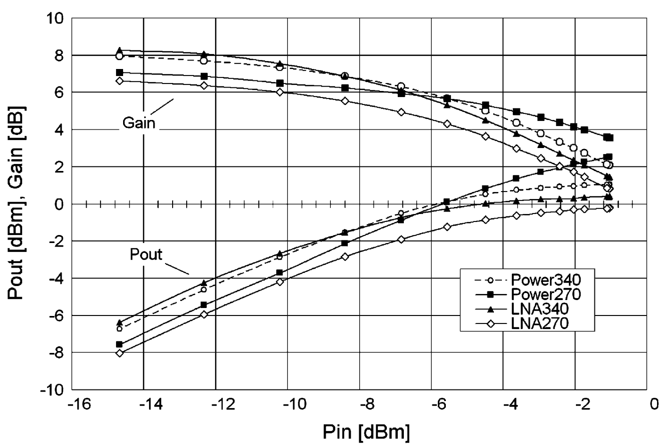

Fig. 5. $P_{\rm in}$ versus $P_{\rm out}$ and gain of different 35 nm InP HEMT amplifiers measured at 330 GHz. Data from the Power270 amplifier is included for comparison.

Fig. 5 shows measured $P_{\rm in}$ versus $P_{\rm out}$ and gain of other amplifiers at 330 GHz.

V. Measurement Errors

Measurement errors can be separated into different components [6]. They are uncertainty in probe loss, uncertainty in partitioning of probe loss, uncertainty in the input power source level, and uncertainty in the calorimeter power measurement. The first two errors affect all measurements systematically. The last two are random, changing as measurements are made. Random errors in the input power source level are due primarily to three errors: irreproducibility of setting the variable attenuator ($\pm$0.015 mW), calorimeter zero drift over the period of tests ($\pm$0.005 mW), and calorimeter meter reading fluctuations during tests ($\pm$ 0.002 mW). Uncertainty from random errors on the output power measurement is due to both the calorimeter zero level drift and meter reading fluctuations. These drift and fluctuations are attributed mainly to thermal variations in the test environment. For deducing total error, the observed random error quantities are combined by quadrature summing and then the systematic losses are arithmetically summed with the random errors to determine the greatest total error.

Fig. 4 shows the total error bars for each data point de-embedded to the input and output of the amplifier that sourced the greatest $P_{\rm out}$ (Power270). The gain error bars are calculated from adding the greatest total errors of $P_{\rm out}$ and $P_{\rm in}$ for the same systematic errors.

VI. Conclusion

We have built a test set and performed the first on-wafer power measurement of a submillimeter wave amplifier. Power measurements at 330 GHz resulted in maximum output power of 2.52 $\pm$ 0.49 dBm (1.78 mW) and maximum gain of 7.07 dB. Measurement errors are attributed to uncertainty in probe loss de-embedded to the amplifier terminals, irreproducibility of setting the variable attenuator for the input power, and variations in the test environment. The results we present are the highest frequency on-wafer power measurements we are aware of reported to date. The method we employ demonstrates a rapid method for evaluating power amplifiers without the need for packaging at these high frequencies.

References

[1] X. B. Mei, W. Yoshida, W. R. Deal, P. H. Liu, J. Lee, J. Uyeda, L. Dang, J. Wang, W. Liu, D. Li, M. Barsky, Y. M. Kim, M. Lange, T. P. Chin, V. Radisic, T. Gaier, A. Fung, L. Samoska, and R. Lai, "35-nm InP HEMT SMMIC amplifier with 4.4-dB Gain at 308 GHz," *IEEE Electron Device Lett.*, vol. 28, no. 6, pp. 470–472, Jun. 2007.

[2] W. R. Deal, X. B. Mei, V. Radisic, W. Yoshida, P. H. Liu, J. Uyeda, M. Barsky, T. Gaier, A. Fung, L. Samoska, and R. Lai, "Demonstration of a 270-GHz MMIC amplifier using 35-nm InP HEMT technology," *IEEE Microw. Wireless Compon. Lett.*, vol. 17, no. 5, pp. 391–393, May 2007.

[3] V. Radisic, X. B. Mei, W. R. Deal, W. Yoshida, P. H. Liu, J. Uyeda, M. Barsky, L. Samoska, A. Fung, T. Gaier, and R. Lai, "Demonstration of sub-millimeter wave fundamental oscillaotrs using 35-nm InP HEMT technology," *IEEE Microw. Wireless Compon. Lett.*, vol. 17, no. 3, pp. 223–225, Mar. 2007.

[4] A. K. Fung, D. Dawson, L. Samoska, K. Lee, T. C. Gaier, P. Kangaslahti, C. Oleson, A. Denning, Y. Lau, and G. Boll, "Two port vector network analyzer measurements in the 218–344 GHz and 356–500 GHz frequency bands.," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 12, pp. 4507–4512, Dec. 2006.

[5] A. Fung, L. Samoska, G. Chattopadyay, T. Gaier, P. Kangaslahti, D. Pukala, C. Oleson, A. Denning, and Y. Lau, "Two port vector network analyzer measurements up to 508 GHz," *IEEE Trans. Instrum. Meas.*, vol. 57, no. 6, pp. 1166–1170, Jun. 2008.

[6] T. Gaier, L. Samoska, C. Oleson, and G. Boll, "On-wafer testing of circuits through 220 GHz," in *Proc. Ultrafast Opt. Electron. Conf.*, Snowmass, CO, Apr. 1999, pp. 20–26.

[7] W. R. Deal, X. B. Mei, V. Radisic, W. Yoshida, P. H. Liu, J. Uyeda, M. Barsky, T. Gaier, A. Fung, L. Samoska, and R. Lai, "A 245-GHz MMIC amplifier with 80-μm of output periphery and 12-dB gain," in *IEEE MTT-S Int. Dig.*, Jun. 2007, pp. 329–332.